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ORIGINAL

FUEL
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January 21st 2000

United States Department of Transportation
Dockets Docket No. F.A.A. 1999-6411—4
400 Seventh Street Room Plaza 401
Washington DC 20590

This is a response to the proposed rulemaking action: "Transport Airplane Fuel Tank Design Review, Flammability Reduction, and Maintenance Requirements."

[4910-13]
Department of Transportation
Federal Aviation Administration
14 CFR Parts 21, 25, 91, 121, 125 and 129
Docket No. F.A.A. –1999-6411; Notice No. 99-18
RIN 2120-AG62

Scope:

The underlying safety issues, uncovered as a result of the TWA 800 crash investigation, have resulted in a new scientific understanding of fuel tank flammability and the risk it presents to commercial flight. Accordingly, the F.A.A. has set forth three proposed amendments to existing regulation and plans to initiate further action to improve and assure better safety. Three immediate changes are proposed to FAR 25.981, which are intended to decrease the risk of fire or fuel tank explosion in transport category airplanes. Amendments one and two, focus on reducing the probability of ignition sources occurring within or near the fuel tanks and set forth increased maintenance efforts to attempt such improved safety. The third proposed amendment seeks to minimize the development of flammable vapours in fuel tanks themselves if ignition should somehow occur despite the increased maintenance.

The Fuel Dynamics, Inc. response:

The thrust of this response aims directly at the reduction of flammability aspects of the F.A.A. NPRM and introduces *POLARJETtm* as a proven, cost-effective means of reducing this ever-present risk in both newly-designed airplanes and in existing airplanes, should an ignition source occur through unanticipated circumstance. Fuel Dynamics, Inc. applauds this unprecedented F.A.A. change in philosophy and timely action in recognizing that, by reducing fuel tank flammability, many lives will be saved during airline incident or accident. Non-flammable fuel tanks will be shown as valuable in saving lives even if the fuel tank itself is not the cause of the accident. A recent example of this deadly risk exposure is the 1999 American Airlines flight 1420 accident in Little Rock, Arkansas.

POLARJETtm.

***POLARJET* is practical, cost effective and a proven factor of safety. It is the world's first thermodynamic (pre-cooled) ASTM D1655 jetfuel. On September 15th 1999 in Fort Worth, Texas, Fuel Dynamics, Inc. re-fueled a turbine powered airplane, (N130RS) publicly demonstrating that the patent-pending thermodynamic fuel process, "*POLARJET*" creates a non-combustible, non-flammable airplane fuel tank while actually improving the economics of operating the airplane. Scientists from the University of North Dakota conducted the sampling and analysis and, with a representative of the F.A.A. W.J. Hughes Technical Center attending, one side of the airplane was comparatively loaded and verified non-flammable alongside a typical re-fueling operation that was found to be flammable. Beyond the obvious safety benefits, the team of University Scientists also documented that 76% fewer polluting VOC emissions were vented during the re-fueling and from the airplane itself thereafter. Claims toward improving the economics of operating the airplane were also shown to be valid.**

Some 25 billion gallons of jetfuel are consumed annually in the United States. Jetfuel vapours are evolved during storage, airplane re-fueling, waiting for takeoff clearance, taxiing and during flight. The presence of jetfuel hydrocarbon (HC) vapours in airplane fuel tank ullages in sufficient concentrations can present an explosion hazard, and venting vapours to the atmosphere is a significant source of ozone-forming hydrocarbon emissions. During hot summer weather, especially in southern climates, fuel vaporization increases in chemical response to both warmer air and warmer fuel. During flight, the risk of flammable air/fuel vapour mixtures occurring in fuel tanks increases dramatically along with increasing altitude and the associated decreasing pressure. If exposed to an ignition source, these ullage atmospheres often contain the right proportions of the flame triangle to support combustion, which can be a single point failure that results in the loss of the airplane. Significantly reducing the magnitude of the fuel's evaporative emissions helps reduce the risk of explosion because fuel cooled below a threshold temperature will generate insufficient hydrocarbon vapour to exceed the lower explosive limit of the fuel, which for jetfuel, ranges from between 5,000 to 6,000 parts per million (ppm) in air. Cooling fuel greatly reduces the rate of HC evaporation and causes the fuel to gain density proportionally with the temperature change. Fuel Dynamics, Inc. of Arlington, Texas, has developed practical technology for cooling jetfuel prior to re-fueling.

Technically, *POLARJET* is a refrigerated ASTM D1655 jet-A fuel that functions as a vapour phase inhibitor to reduce hydrocarbon evaporation, rendering fuel tanks non-combustible, non-flammable and less polluting. Jetfuel has always been considered flammable when temperatures are in excess of 100°F at sea level pressure. However, it is now understood that when exposed to the reduced pressures of altitude, jetfuel is flammable at any temperature greater than 45°F. Therefore, with modern industrial cooling equipment applied, it is now reasonable to look at reducing or refrigerating jetfuel to temperatures less than 30°F before flight on a nation-wide basis. Normally supplied to airplanes at temperatures of more than 110°F it is easy to understand the immediate safety advantages of loading a "cooled fuel." However, there are advantages that extend well beyond the improved fire safety.

An economic advantage exists. When cooled, jetfuel becomes more dense, and it becomes possible to load more fuel energy aboard the airplane which opens many new options for the airplane operator. Having more energy uploaded aboard the airplane allows greater flight endurance and this can result in a substantial improvement to the economics of operating the airplane. Ultimately by cooling the fuel, it is possible to extend the endurance of the airplane by up to an additional hour and at cruising speed, this new level of safety becomes a cost-effective and even a cost-saving, advantageous tool for the airline. By extending endurance, additional destinations can be reached, pilots will have more fuel available for diversions and many difficult upwind routes will become nonstop through re-dispatch procedures. It has been estimated that by eliminating a single re-fueling tech-stop, a B-747 flying upwind from Chicago to Hong Kong can save $72,000.00 per flight by loading *POLARJET*. Additionally, what is an extra half hour worth when a pilot can remain in a weather holding pattern a bit longer and possibly avoid diverting his entire planeload of passengers to a diversion airport?

The petroleum industry has refined the manufacture of jetfuel into a practical commercial commodity that satisfies all technical engineering concerns. Years of development have resulted in a fuel that can be depended upon and it performs well. Therefore, to gain immediate acceptance, the composition of ASTM D1655 jetfuel must not change. The *POLARJET* process does not alter the ASTM D1655 composition in any way, but it clearly does make jet-A fuel much more valuable.

Having a "cold fuel" on turbine powered airplanes is an everyday circumstance. With flight conditions naturally being cold at altitude, fuel normally cools to frigid temperatures during later portions of flights and aircraft systems are specifically designed to consume and burn this frigid fuel. Therefore, it can be said that *POLARJET* simply creates these very same, more-safe cold temperatures - earlier in the flight envelope. *POLARJET* presents no operational problems outside those typically encountered in today's airplane operation.

The N.T.S.B, F.A.A. and EPA are aware of the *POLARJET* process and its demonstrated performance. The F.A.A. has determined that as *POLARJET* is not in any way unusual to the turbine powered airplane, is within airplane temperature design standards and requires no airframe or powerplant modification, it meets all existing federal regulation for immediate use. The N.T.S.B. has reviewed *POLARJET* data and has said that this technology is something that needs to be looked at to improve safety. The EPA is aware of the *POLARJET* process, applauds our effort and is reviewing the impact of a seventy-six percent (76%) reduction of VOC emissions on overall clean air status and the impact of regulatory compliance. The military has interest, but our efforts have been directed almost exclusively toward benefiting the commercial air carriers.

Unobtrusive commercial airline systems are under development and a full size, completely self-contained prototype unit is available from Fuel Dynamics, Inc. for immediate demonstration and/or testing. This prototype (photos enclosed) can service any turbine powered airplane - small business jet through the heavy class jets. Extremely unobtrusive commercial systems will supply both truck-delivered and hydrant airports, and flow rates will meet even the heaviest simultaneous airline expectations. Small, medium and large FBO and privately owned systems will be made available for business jets and airfreight carriers. Implementation is possible on selected major airports within two years, and a reasonable coverage of the remaining airports can be complete within five years. While a detailed study is necessary, it is believed that costs before airline savings are realized, will amount to approximately one penny per gallon, or the equivalent. Several airlines have shown interest, especially in the endurance benefits and Airbus has indicated that a no technical objection (NTO) statement would be issued to any airline making a request. Having a massive cooling capability on a heavy use airport will also relieve other hard to cool airport structures and further assist in diluting equipment installation and operational costs.

It has been discussed at various levels that a structure exists within the federal framework to pass the cost of passenger safety improvements such as *POLARJET*, directly to the airline passenger.

Previous surveys have clearly indicated that passengers would be willing to pay more per seat for improved fire safety. In very rough numbers, if it were decided that the cost of this new safety was to be placed entirely upon the airline passenger, *POLARJET* could flow at an airport like DFW Airport for less than a dollar per seat.

***POLARJET* technology was not timely unveiled to or seriously considered by the 1998 A.R.A.C. Fuel Tank Harmonization Working Group. Therefore, without having the critical facts and benefits of *POLARJET* before them, Fuel Dynamics, Inc. is convinced that the 1998 ARAC FTHWG report incorrectly concluded that reducing flammability onboard the airplane is not economically practical across *both* the new and existing fleet of commercial airplanes. Further, with all considered at that time, it was determined that placing passenger aircraft at a 7% overall exposure to flammability would be acceptable. Fuel Dynamics, Inc. strongly disagrees with this finding as it has been since accepted that it is impossible to preclude all possible ignition sources within or near airplane fuel tanks, therefore this acceptance to risk is most unwise.**

Apparently, the A.R.A.C. decision to accept this 7% risk was based on the historical lack of explosive events occurring in airplane wing structures. In these records, wings have shown a general 5% exposure to combustible vapours as compared to an approximate 30% exposure for the center wing tanks. Fuel Dynamics, Inc. believes that the more-safe wing structures strongly evidence the inherent safety of a "cooled fuel" as they are almost immediately exposed to cold temperatures in flight. Wing structures cool much faster in flight, and offer a representative sample of the inherent safety of *POLARJET*. If *POLARJET* were used by the commercial carriers across the board, on all flights, it would be possible to create better safety onboard airplanes than the 7% time at exposure to explosive conditions goal offers. Further, this safety should be made available to not only the newly designed airplanes, but also to the existing fleet. The turbine powered regional airplanes and corporate jets, specified as less than 30 seats and having less than 7,500-lbs. gross weight are at the very same risk as the larger airplanes and should not be exempt from attaining this safety.

While TWA 800 investigators cannot specifically identify the precise ignition source of the explosive fuel tank event that brought about the loss of the airplane, the glaring fact remains that if the fuel tank had been made non-combustible, the explosion would simply not have occurred. The N.T.S.B. has determined that fuel tank events occur every 2.6 years. *POLARJET* safety is needed right now.

Certain operational circumstances require that CWTs be carried with only unusable fuel supplies remaining (empty) and these conditions create enormous volatility, especially when exposed to natural (solar) and onboard heat sources. (any onboard system that adds heat to the fuel system) Some airplanes have heat exchangers operating inside fuel tanks that use onboard fuel supplies as a convenient heat sink. To remedy these highly unstable "empty tank" circumstances, the flow of cold *POLARJET* can be injected with an inert gas and the flow through the tanks and ullages managed to provide an inerted empty tank. The gas will sufficiently dilute the ullage oxygen to levels that will not support combustion which makes empty fuel tanks non-combustible as well. As airplane fuel tanks are open vented to relieve pressures within during flight, and it is desirable that no modifications are to be made to the airplane, the tanks must remain open vented, which will slowly allow the available atmosphere to re-enter the oxygen-lean ullage during flight. Our testing has shown that while nitrogen is effective on a very short term basis in open vented fuel tanks, it does not have the atomic mass required to maintain non-combustible levels over reasonable periods of time. It is thought however, that another noble inert gas, one with a greater atomic mass - will be sufficient to maintain a non-combustible environment.

Reasonable concern has been expressed about the cooled fuel expanding onboard the airplane and ultimately overflowing through vents during flight delays. The rate of *POLARJET* expansion is very slow even in the hottest weather, and is expected to be such that will allow up to a 5 hour launching window after refueling and the fuel burn of just one engine or auxiliary power unit (APU) will extend this window indefinitely. As *POLARJET* warms it expands and it expands into the fuel expansion space allowed (≥2%) for fuel expansion onboard the airplane. Should the airplane experience an extensive delay, one where the engines and APUs must be shut down, the expansive amount

will need to be de-fueled to prevent overflow. Accordingly, timely re-fueling practices must be adopted.

Fuel Dynamics, Inc. is prepared to take all necessary action to have *POLARJET* become rapidly established as an acceptable means of achieving a practical, cost-effective reduction of flammable vapours onboard newly designed and existing fleets of airplanes. *POLARJET* could be considered a cost effective, cost saving, practical form of ground based inerting.

In that the F.A.A. has acknowledged that any fuel temperature in excess of 45°F is flammable at altitude, Fuel Dynamics, Inc. suggests that the following safety precautions be considered as a means of compliance to this SFAR and any subsequent reduced flammability regulation. Further, it may be appropriate to mandate these changes to assure safety. Fuel Dynamics, Inc. suggests that specific wording of subsequent FARs regulation should include language specifying that:

1.) **Fuel temperature may not exceed 30°F while onboard turbine powered airplanes during operation, including pre and post flight operations.**

2.) **Jet-A fuel shall be cooled to temperatures less than 30°F before flight.**

3.) **If aircraft systems add heat energy to the onboard fuel tanks, fuel should be loaded at temperatures sufficiently reduced to achieve an equilibrium fuel temperature of no greater than 30°F within the airplane.**

4.) **If aircraft are on hold before takeoff, and airport conditions (solar heating) or onboard systems use the fuel supply on the airplane as a heat sink to dissipate systemic heat, or otherwise radiate heat into the onboard fuel, the fuel supply must be recirculated through appropriate heat rejecting equipment to maintain an onboard fuel temperature of no greater than 30°F.**

5.) **Any aircraft having onboard systems (i.e. MD-80) intended to elevate fuel tank temperatures to offset the occurrence of clear ice, black ice, frost or any other form of ice which may enthalpy on wingskins as a result of the phenomenon of cold soaked fuel causing ice, shall be able to regulate these fuel temperatures and no fuel temperature shall exceed 30°F during any portion of the flight or preflight operation.**

6.) **No airplane may systemically elevate onboard fuel supplies to temperatures greater than 30°F for any reason.**

Conclusion

Fuel Dynamics, Inc. has publicly demonstrated that *POLARJET*tm is effective and aligns well with N.T.S.B. recommendations: A-96-174, A-96-175, A-96-176 and with F.A.A. AD98-08-09 in regard to immediately reducing explosive fuel/air rations within fuel tanks. (A University of North Dakota Energy and Environmental Research Center Final Report is attached for review.) *POLARJET* can and will provide immediate safety not only preventing fuel tank related events, but it will also save lives by retarding flame propagation and flash fires during any incident or accident whether the accident is fuel tank caused or not. A current example of this circumstance is the American Flight 1420 crash in Little Rock. In this crash, a MD-82 center fuel tank was likely superheated by onboard fuel heating systems during delay at DFW and was of extremely condensed vapours upon arrival in Little Rock. These highly flammable condensed vapours combined with oxygen upon structural failure and when exposed to the many ignition sources of the accident, produced a flash fire and numerous loss of life.

POLARJET is not a magic fuel additive. It is simply the application of simple thermodynamic physics to jetfuel and a practical new degree of cost effective and even cost saving safety through creating better flight endurance. *POLARJET* represents the birth of a new advantageous service industry to the airlines. Fuel Dynamics, Inc. believes that *POLARJET* is the only practical solution to fuel tank flammability as it brings no additional airplane complexity, no weight penalty, no F.A.A. re-certification issues and no additional airplane maintenance.

POLARJET is worldwide patent-pending and is the exclusive licensed property of Fuel Dynamics, Inc. We believe that airline operations could and should voluntarily justify using cooled *POLARJET* and the goal of Fuel Dynamics, Inc. is to make air travel more safe with the expense to the airline being offset through better flight performance.

***POLARJET* should not be seen as having any cost as it saves dollars through increasing the endurance of the airplane. Fuel Dynamics, Inc. is convinced that it is possible to prevent the next fuel tank accident from occurring.**

Fuel Dynamics, Inc. / POLARJET

Attachments: University of North Dakota/ EERC POLARJET testing report
Photo of September 1999 public re-fueling demonstration

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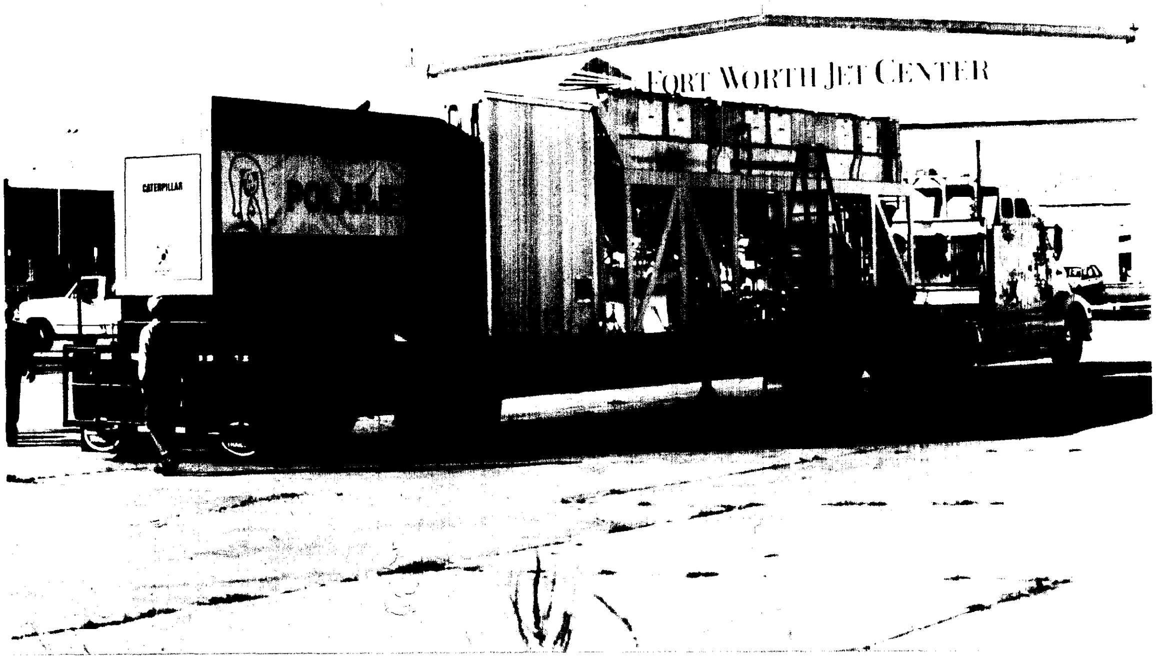

Energy & Environmental Research Center

FLIGHT SAFETY, ENDURANCE, AND EVAPORATIVE EMISSIONS IMPROVEMENT VIA JET FUEL-COOLING — POLARJET™ FUEL TREATMENT DEMONSTRATION

Final Report

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October 1999

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INTRODUCTION

About 25 billion gallons of jet fuel is consumed annually by the U.S. aviation industry. Jet fuel vapors are evolved during aircraft refueling, waiting for takeoff clearance, taxiing, and flight. The presence of jet fuel hydrocarbon vapors in aircraft "ullage" (the headspace above the liquid fuel in a tank) in sufficient concentrations can present an explosion hazard, and venting of jet fuel vapors to the atmosphere is a significant source of ozone-forming hydrocarbon emissions. During hot summer weather, especially in southern climates, fuel vaporization increases in response to both warmer air and warmer fuel, and during flight, the risk of flammable air–fuel vapor mixtures occurring in fuel tanks increases along with increasing altitude and decreasing pressure. Significantly reducing the magnitude of these emissions would help reduce the risk of explosion because fuel cooled below a threshold temperature will generate insufficient hydrocarbon vapor to exceed the lower explosive limit of the fuel, which, for jet fuel, generally ranges from about 5000 to 6000 parts per million (ppm) in air. Fuel Dynamics Inc. of Arlington, Texas, has developed Polarjet™ technology for cooling jet fuel prior to aircraft refueling. The technology enables normal flow rate refueling with fuel cooled to a specified temperature.

BACKGROUND

The University of North Dakota Energy & Environmental Research Center (EERC) and the John D. Odegard School of Aerospace Sciences (OSAS) in Grand Forks, North Dakota, were contracted by Fuel Dynamics to help demonstrate and measure the effect of Polarjet fuel cooling on reducing jet fuel vaporization. Cost share for the project was provided by the U.S. Department of Energy-funded EERC Jointly Sponsored Research Program. The project objective was to compare Polarjet-treated fuel to untreated, ambient-temperature fuel on the basis of ullage hydrocarbon vapor and oxygen concentrations using a jet aircraft with two separate (right- and left-side) fuel tank systems. This objective was achieved in a Polarjet demonstration conducted using a Learjet at the Fort Worth Jet Center, Fort Worth Meacham International Airport, on September 15, 1999.

ANALYTICAL METHOD DEVELOPMENT

Prior to the demonstration, two portable infrared spectroscopic analysis systems for measuring oxygen and hydrocarbon levels in a fuel tank were procured and calibrated for Jet A fuel. Each system comprised a Summit™ FGA 4005 five-gas exhaust emissions analyzer interfaced to a laptop personal computer (PC). The Summit analyzer is equipped with a pump that draws vapors through an infrared beam and a chemical cell for hydrocarbon and oxygen concentration determination, respectively. Also interfaced to the same PC was a vapor and liquid temperature-monitoring system comprising two thermocouples wired into a Fluke™ Hydra 2625 data logger. Computer control of both systems enabled the acquisition of real-time in-tank hydrocarbon and oxygen concentration and fuel liquid and vapor temperature data at specified time intervals. To shake down the systems, tests were performed using a 30-gallon aluminum aviation fuel tank containing 5 gallons of Jet A fuel. The tank was placed outside under sunlight at an ambient temperature of approximately 91 °F, and hydrocarbon and oxygen concentrations and liquid and vapor temperatures were monitored. Resulting data are provided in Table 1.

For comparison, Table 1 also shows approximate hydrocarbon and vapor temperature data acquired in a National Transportation Safety Board (NTSB)-funded project. In the NTSB project, vapors from the center wing tank of a Boeing 747-100 jet were sampled and analyzed as part of an effort to simulate operating conditions just prior to Accident DCA96MA070 (the crash of a 747-131, N93119, operated as TWA Flight 800). The NTSB data were acquired and reported by the Desert Research Institute in Reno, Nevada (1). The NTSB hydrocarbon data as shown in Table 1 are approximate values based on conversion of part-per-thousand – carbon basis concentrations to part-per-million – compound basis concentrations. Although the NTSB data were acquired under significantly different conditions (including heat input from several different on-board sources) and were not reported with associated liquid fuel temperatures, comparison of the EERC and NTSB hydrocarbon data for similar vapor temperature ranges provides a reasonable corroboration of the EERC sampling and analysis methodology.

POLARJET DEMONSTRATION

Polarjet and analytical systems shakedown tests were performed on September 14, and Polarjet demonstration tests were performed on September 15, 1999. All tests were performed at the Fort Worth Jet Center in Fort Worth, Texas, using 1968 a Lear 24 jet aircraft with wing and tip tanks. Throughout all shakedown and demonstration tests, the aircraft was oriented with left (port) wing approximately west–southwest and right (starboard) wing east–northeast. Prior to initiating testing on September 14, both left and right tanks were drained to as low a liquid level as possible, which, according to standard aviation industry practice corresponds to the "level of only unusable fuel remaining." The analytical systems were installed in the drained tip tanks, and baseline hydrocarbon and oxygen data were acquired. These baseline data are listed in Table 2 and illustrated in Figures 1 and 2.

On the afternoon of September 15, several Polarjet demonstration tests were performed. Two key tests are reported here. During the tests, ambient temperature rose steadily from 84° to 88°F, pressure dropped steadily from 30.07 to 29.99 in. of mercury, and skies were mostly sunny. The Jet A fuel used in both tests had minimum and maximum flash points of 100° and 132°F (as per Method D56) and contained 1 gallon per thousand of Prist (an additive designed to prevent fuel icing and bacteria growth). In both tests, fuel was loaded at a rate of 15 gallons per minute in accordance with Learjet-specified procedures. In the first test, both tanks were drained to the level of only unusable fuel remaining, and 240 gallons of Polarjet-treated 7°F fuel were dispensed into the empty right tanks through the tip tank fill spout, while 240 gallons of ambient-temperature fuel were simultaneously dispensed into the empty left tanks through the tip tank fill

TABLE 1

Jet A Hydrocarbon and Oxygen Concentration versus Temperature

Liquid Temperature, °F	Vapor Temperature, °F	Hydrocarbon Concentration, ppm	Oxygen Concentration, vol%
87	102	2660	20.8
95	112	4850	20.8
99	117	4760	20.9
105	119	5470	20.7
110	120	5870	20.8
112	114	6530	20.8
Unreported	114[1]	5730[1]	Unreported
114	117	6310	20.7
117	118	6890	20.7
119	118	6600	20.6
Unreported	120[1]	6120[1]	Unreported
Unreported	123[1]	7110[1]	Unreported

[1] Data from NTSB (1).

TABLE 2

Polarjet Demonstration Data

Test Description				Liquid Temperature, °F		Vapor Temperature, °F		Hydrocarbon Vapor, ppm		Oxygen Content, vol%	
Test	Tank	Contents, gallons	Duration, minutes	Minimum/ Maximum	Average	Minimum/ Maximum	Average	Minimum/ Maximum	Average	Minimum/ Maximum	Average
Baseline	Left	Empty[1]	2	92/94	93	92/92	92	3846/4342	4094	20.5/20.7	20.6
Baseline	Right	Empty[1]	2	91.5/91.7	91.6	90.4/90.3	90.3	3984/4062	4023	20.6/20.8	20.7
Ambient	Left	240	31	90/91	91	95/99	98	3907/5247	5061	20.4/20.6	20.5
Polarjet	Right	240	26	7.1/22.3	14.7	62.1/78.1	70.1	1094/1232	1201	20.5/20.8	20.7
Polarjet + N_2	Right	240 + 20 with N_2	19	35.4/40.3	37.9	71.9/78.7	75.3	1280/1667	1435	14.4/20.7	18.9

[1] Tanks were drained to level of only unusable fuel remaining.

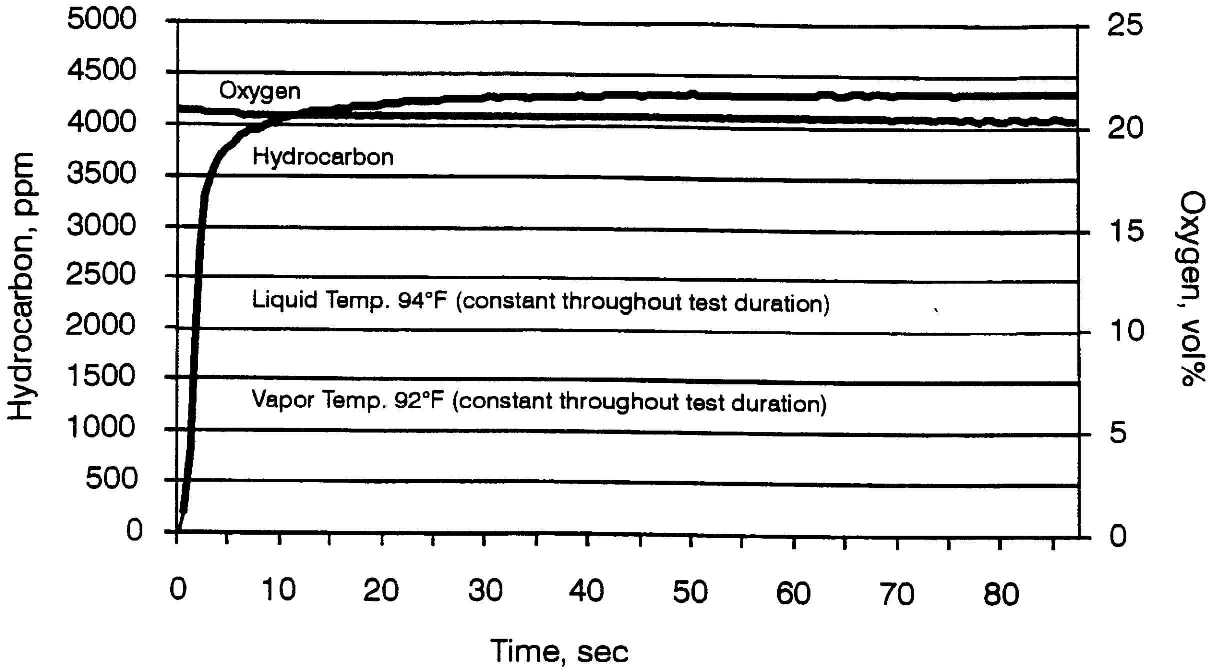

Figure 1. Hydrocarbon and oxygen concentration versus time for empty left-side tank (data acquired to establish in-tank baseline conditions for demonstration tests).

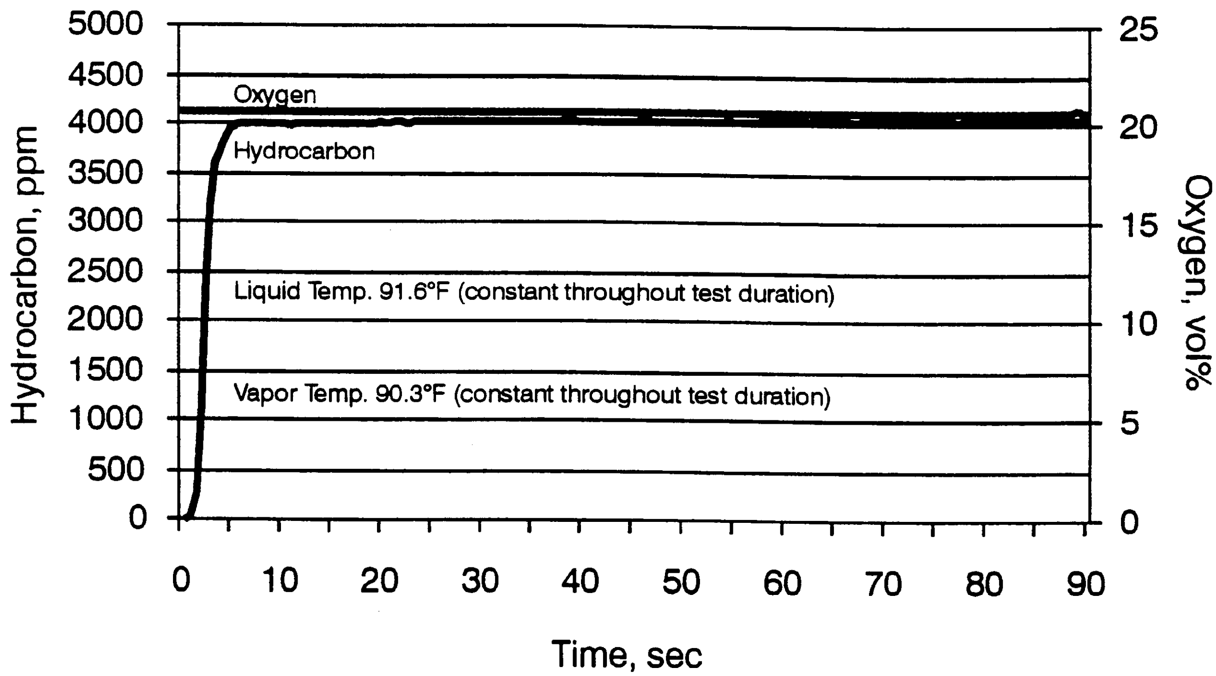

Figure 2. Hydrocarbon and oxygen concentration versus time for empty right-side tank (data acquired to establish in-tank baseline conditions for demonstration tests).

spout. Simultaneous hydrocarbon, oxygen, and temperature data were acquired for the left and right tanks. These data are displayed in Table 2. Figure 3 compares hydrocarbon concentrations in Polarjet and ambient fuel ullages, and Figure 4 illustrates the relationship between temperature and hydrocarbon concentration in ambient and Polarjet ullages, and how the vapor concentrations in each tank compare to a published Jet A lower explosive limit (LEL) hydrocarbon concentration of 5000 ppm (2). A definition of LEL and discussion of how LEL affects fuel explosion hazard is provided in the following section of this report.

POLARJET VERSUS AMBIENT FUELING

Jet A is a mixture of hydrocarbon molecules of various sizes. As the temperature of liquid Jet A in a tank is increased, increasing numbers of molecules volatilize (or vaporize) from the liquid, resulting in a higher concentration of fuel vapors in the tank ullage. For every liquid hydrocarbon fuel, including Jet A, a minimum vapor concentration exists, above which the presence of an ignition source will result in an instantaneous combustion or explosion of the fuel vapor. This minimum vapor concentration is called the fuel's LEL. For most Jet A fuels, the LEL (in atmospheric air with an oxygen concentration of about 20.7 volume percent) is in the range of 5000 to 6000 ppm of hydrocarbon molecules (2, 3). At fuel vapor concentrations below the LEL, combustion will not occur. Figure 4 illustrates that while the ambient-temperature fuel generated hydrocarbon vapors at concentrations near the Jet A LEL, the Polarjet fuel vapors were present in concentrations well below the LEL.

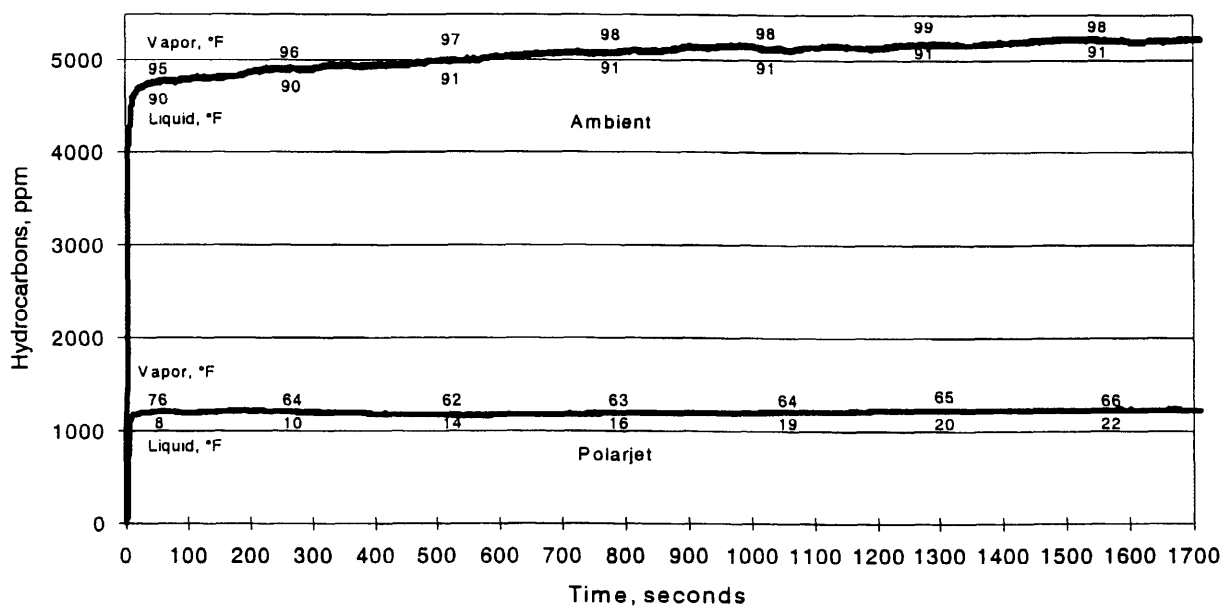

Figure 3. Hydrocarbon concentration versus time in left- and right-side tank ullages above ambient-temperature and Polarjet-cooled fuels, respectively. Also shown are periodic liquid and vapor temperature measurements.

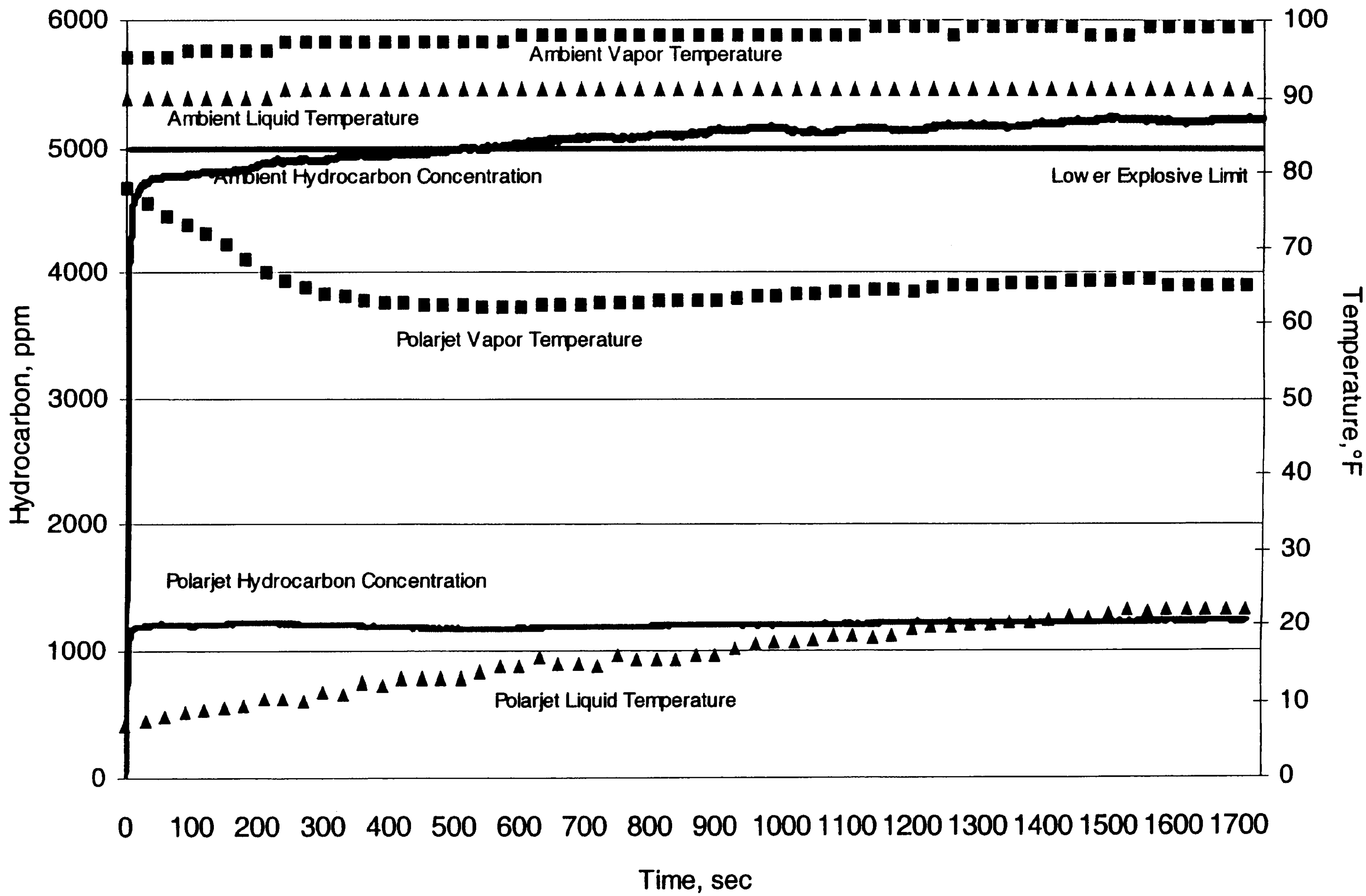

Figure 4. Hydrocarbon concentration and liquid and vapor temperature versus time for ambient-temperature and Polarjet-cooled fuel ullages (includes Jet A lower explosive limit hydrocarbon concentration for comparison).

Another way to assess fuel flammability is lower flame propagation limit (LFPL). As reported by the Fédéral Aviation Administration (4), the LFPL for Jet A fuel is 0.03 kilograms fuel per kilograms air (kg fuel/kg air). When a fuel–air mixture equals or exceeds this concentration in the presence of an ignition source, combustion can occur. Table 3 shows that the fuel–air ratio in the ullage of a tank filled with Jet A at ambient temperature was 77% of LFPL, while the fuel–air ratio for the Polarjet ullage was only 18% of LFPL. Because fuel vapor concentration in a tank ullage is primarily dependent on liquid fuel temperature, the Polarjet-cooled fuel provided a wide margin of safety based on LFPL.

In addition to LEL and LFPL, another requirement for combustion is ignition temperature (T_i), which, for a typical Jet A fuel is about of 380°F (2). To sustain or propagate combustion requires that the temperature of molecules adjacent to the combustion process (the flame) are at least as hot as T_i. When a fuel mixture has reached its T_i near an ignition source, combustion begins, with the flame achieving a temperature of between 2000 and 3500K (3100°–5800°F). To maintain or propagate combustion, the heat flux from the burning fuel must be sufficient to maintain T_i in the surrounding molecules. When heat flux is inadequate to maintain T_i, flame propagation does not occur and combustion is quenched.

Table 2 shows liquid and vapor temperatures for Polarjet-cooled and ambient-temperature fuels. The data indicate an approximate 28°F difference in vapor temperature and a more substantial 76°F difference in liquid temperature between the Polarjet-cooled and ambient-temperature fuels. The significance of these temperature differences, especially between the liquids, is that in the event of an ignition, the igniting vapors are consumed by combustion, and because more vapors are immediately needed to ensure flame propagation, the lower the temperature of the liquid fuel from which vapors are generated, the greater the possibility of insufficient vapor generation for flame propagation. Research is needed to corroborate the level of explosion hazard reduction achievable through reduction of liquid fuel temperature.

TABLE 3

Fuel Vapor-to-Air Mass Ratio (F/A) Comparison

Fuel Treatment	Tank	Vapor Temperature, °F	F/A, kg fuel/kg air
Ambient	Left-side wing	98.0	0.0232
Polarjet	Right-side wing	70.1	0.0055
Polarjet + Nitrogen	Right-side wing	75.3	0.0066
LFPL	Not applicable	See Reference 4	0.03[1]

[1] As published in Reference 4.

POLARJET PLUS NITROGEN

In the second demonstration test conducted on September 15, pressurized nitrogen gas was blended with Jet A in the Polarjet unit, and approximately 20 gallons of nitrogen-containing 7°F fuel were added to the 240 gallons of Polarjet fuel remaining in the right tanks from Test 1. Addition of the nitrogen-injected fuel to the tank was accompanied by nitrogen offgassing, producing a light fog as the nitrogen bubbled out of solution. Hydrocarbon, oxygen, and temperature data for this test are listed in Table 2. Figure 5 compares hydrocarbon concentrations in Polarjet + nitrogen and ambient fuel ullages (using ambient data from Test 1), and Figure 6 illustrates the relationship between temperature and hydrocarbon concentration in the Polarjet + nitrogen ullage. Figure 7 compares oxygen levels measured in ambient, Polarjet, and Polarjet + nitrogen ullages and shows that the effect of nitrogen addition is relatively short-lived. Although a significant initial oxygen level reduction (from about 20.7 vol% down to about 14.4 vol%) was achieved, oxygen infiltration brought the ullage oxygen level back up to over 19 vol% within 5 minutes (300 seconds). These data indicate the difficulty in maintaining a nitrogen "blanket" in a vented tank, due largely to the fact that nitrogen, with a molecular weight of 28 atomic mass units (amu) is lighter than oxygen, which has a molecular weight of 32 amu.

Figure 8 is a more detailed graph of temperature versus time for the Polarjet + nitrogen test that enables calculation of a heatup rate. The graph shows that during a 735-second (12.3-minute) exposure to approximately 87°F Texas sunshine, fuel with an initial temperature

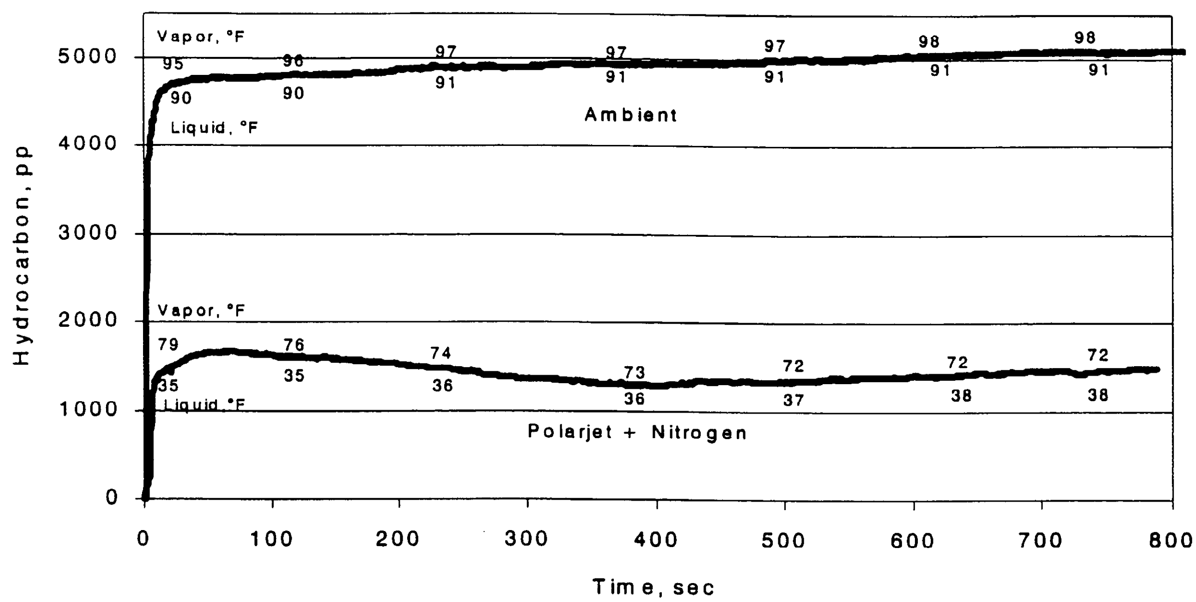

Figure 5. Hydrocarbon concentration versus time in left- and right-side tank ullages above ambient-temperature and Polarjet-cooled plus nitrogen-injected fuels, respectively. Also shown are periodic liquid and vapor temperature measurements

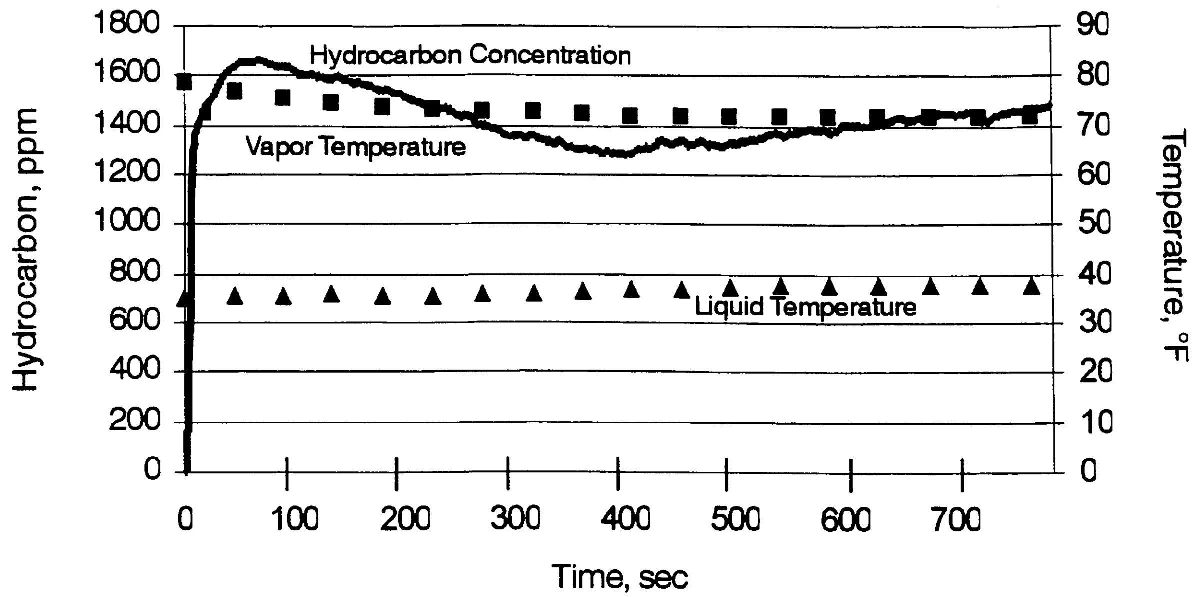

Figure 6. Hydrocarbon concentration and liquid and vapor temperature versus time for ambient-temperature and Polarjet-cooled plus nitrogen-injected fuel ullages.

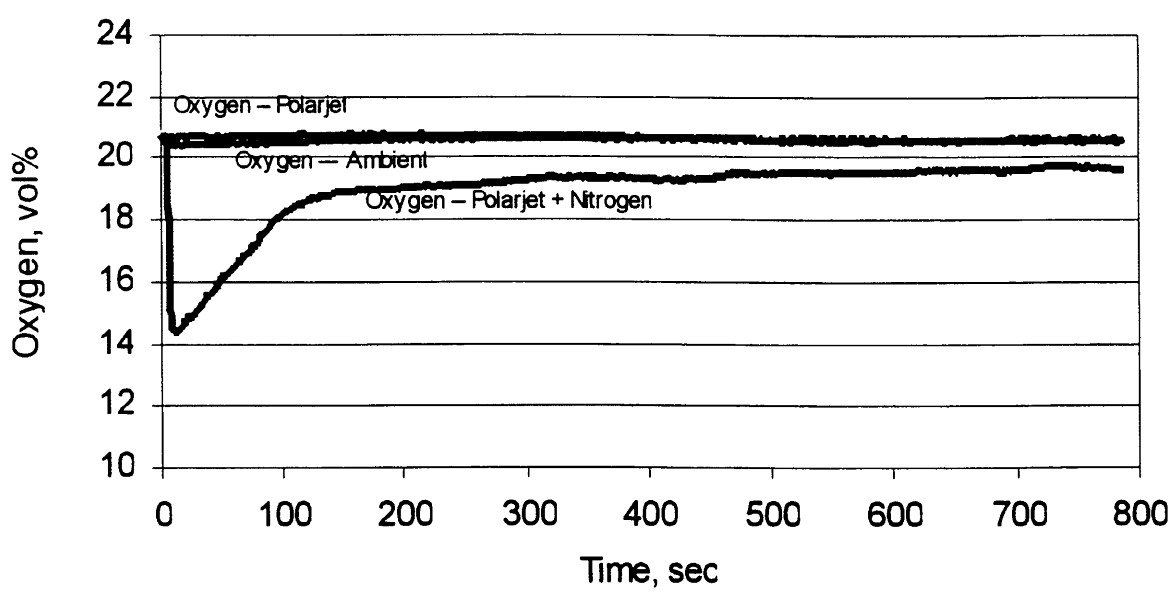

Figure 7. Oxygen concentration versus time for ambient-temperature, Polarjet-cooled, and Polarjet-cooled plus nitrogen-injected fuel ullages.

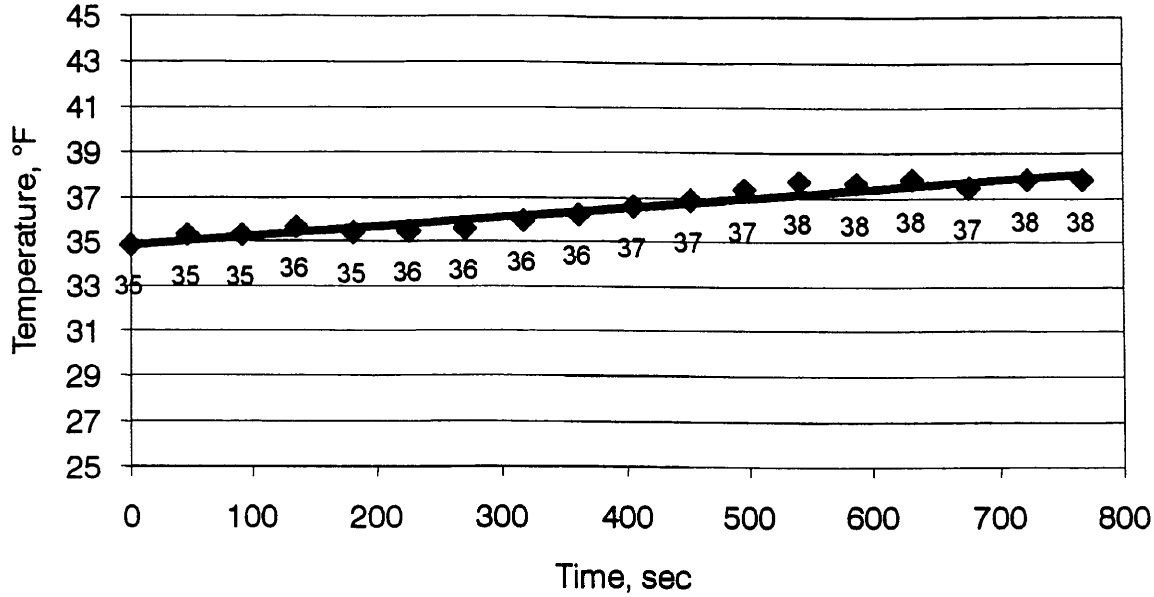

Figure 8. Polarjet-cooled plus nitrogen-injected fuel – liquid temperature versus time.

of 35 °F was heated to a temperature of 38 °F. On the basis of these data, a fuel heatup rate of 14.6 °F per hour is calculated. It is important to consider that this heatup rate is specific to the plane used in this demonstration and is not likely to apply to larger aircraft with significantly different tank configurations and tank surface area-to-volume ratios.

CONCLUSIONS

The data collected during the September 15 Polarjet process demonstration indicate that cold fuel provides a significant margin of safety with respect to explosive fuel–air mixtures in an aircraft fuel tank. The demonstration showed that Polarjet-cooled fuel dispensed into the right-side tank of a Lear jet generated an ullage hydrocarbon concentration of 76% less than ambient-temperature fuel simultaneously dispensed into the left-side wing tank. The data acquired indicated that while fuel vapors in the ambient-temperature fuel tank ullage approached or exceeded the concentration required for combustion—depending on whether LFPL or LEL is used to gauge explosivity—vapors in the Polarjet-cooled fuel tank ullage were present at levels well below combustible concentration regardless of which criterion is used.

The achievement of significant reduction in fuel tank vapor concentration has implications for safety during on-ground activities as well as during flight, especially immediately after takeoff when rapidly decreasing pressure (with increasing altitude) can combine with hot fuel to generate tank ullage hydrocarbon concentrations significantly higher than those observed on the ground. Figure 9 provides an estimate of how 30 °F fuel would compare to hotter fuels based on

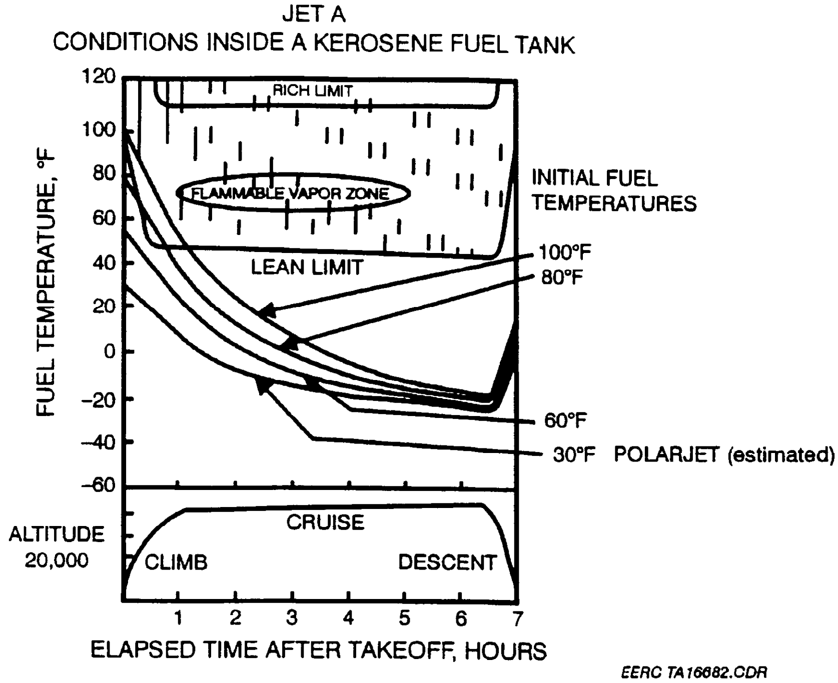

Figure 9. Typical Jet A fuel temperatures in flight of jet transport cruising at 525 miles per hour (based on Boeing Airplane Company and Dehavilland Aircraft Company, Ltd., data, and including estimated effect of 30 °F fuel – original diagram in Reference 4).

flammability hazard over the course of an entire flight from takeoff to landing. As shown in the diagram, fuels present in an aircraft tank at temperatures exceeding about 60 °F will generate flammable vapor concentrations in the tank ullage for varying time periods occurring after take-off and prior to achieving cruise altitude, at which point cold temperatures act to reduce vapor concentrations to levels below the flammable limit, while fuel cooled to temperatures below 60 °F should not generate flammable vapor concentrations at any point during flight. The diagram also indicates that even on the ground, a fuel liquid temperature of about 90 °F is sufficient to generate a flammable vapor mixture. In addition to safety implications, the capability to reduce fuel volatility can provide significant reductions in ozone-forming volatile organic compound (VOC) emissions and provide a reduced occupational hazard to aircraft refueling personnel.

To address the possibility of unforeseen Polarjet treatment-induced changes to Jet A, samples of treated and untreated fuels were collected and analyzed at the EERC for hydrocarbon composition and water content. Gas chromatographic analysis of the two fuels indicated no detectible differences in composition, and the water contents of the two fuels were essentially identical, at 0.0065% and 0.0069% for the untreated and Polarjet-treated fuels, respectively. Specific gravity measurements were performed at the EERC on untreated Jet A cooled to 5 °F (the approximate temperature of Polarjet-treated fuel dispensed into the demonstration aircraft – the actual temperature was 7 °F), Jet A heated to about 95 °F (the approximate temperature observed for the ambient fuel used in the demonstration – the actual temperature was about 91 °F), and Jet A at 73 °F). Specific gravity values of 0.825, 0.805, and 0.796 were determined for the 5°, 73°, and 95°F fuels, respectively, indicating an approximate 3.6% increase in density for the 5°F fuel compared to the 95°F fuel. It is likely that this density change is specific for the fuel tested and that different Jet A fuels would undergo different temperature-derived density changes, depending on fuel chemistry.

To provide context for the findings discussed in this report, Figure 10 presents a composite of EERC and NTSB hydrocarbon–temperature data. In viewing this graph, it is important to realize that the EERC and NTSB tests were conducted under significantly different conditions, two of which are the likely much different surface area-to-volume ratio of the Learjet used in the EERC tests compared to the 747 used in the NTSB tests, and the presence of operating environmental conditioning system (cabin air-conditioning) packs on the 747 during testing. Figure 11 is a plot of calculated vapor concentration versus temperature for decane, a primary constituent of Jet A. It is likely that under controlled conditions, a similar plot for Jet A tank ullage vapor concentration versus temperature would be similarly curvilinear.

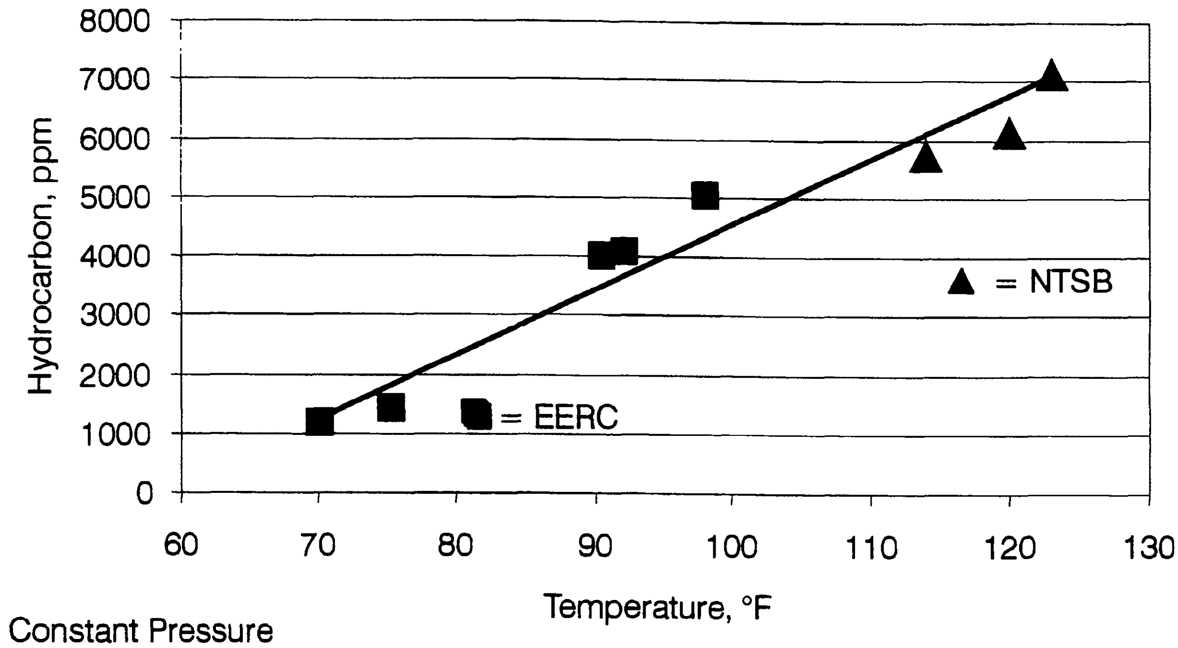

Figure 10. Hydrocarbon concentration versus vapor temperature – EERC Learjet data compared to NTSB Boeing 747 data from Reference 1.

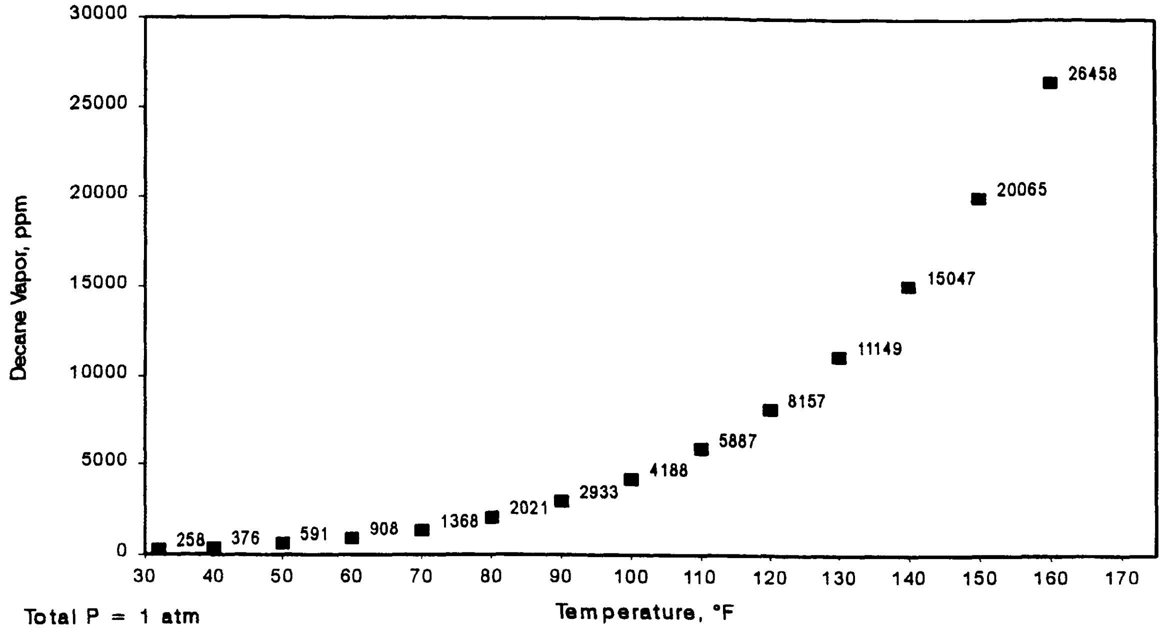

Figure 11. Calculated decane vapor concentration versus temperature. Decane, a 10-carbon molecule, is the primary constituent of Jet A vapors, and the average carbon number of all molecules in Jet A vapors is 9.58 (as reported in Reference 1).

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